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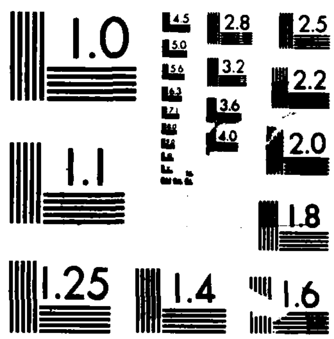
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INSULATED TENTS FOR COLD WEATHER OPERATIONS (U)

by

Brad Cain

DEFENCE RESEARCH ESTABLISHMENT OTTAWA
REPORT NO. 957

Canada

April 1987
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Environmental Protection Section
Protective Sciences Division

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ABSTRACT

Analyses of the insulation requirements and ventilation rates for small, insulated tents were made and compared with both laboratory and field observations on two proto-type tents used during a winter trial. Predicted values of thermal resistance were in good agreement with measured values, although it was found that construction techniques could significantly alter the value of thermal insulation for the tent. Two analyses of the ventilation rate were made, one based on the conservation of thermal energy and the second based on a bouyancy driven pipe flow analysis. Predicted ventilation rates agreed with measured values to within a factor of two under calm conditions. An estimate of the minimum acceptable ventilation rate was made based on a stoichiometric combustion analysis of a generalized hydrocarbon fuel. It was found that, for the insulated tents studied, this minimum ventilation rate could be achieved by natural convection alone. This may not be the case for uninsulated tents as resulting tent air temperatures may be insufficient to produce adequate natural convection ventilation. Observations of carbon monoxide levels, made while heating the tents during the winter trial, indicated that the levels where well within acceptable occupational levels and often within acceptable public exposure levels. The use of insulated tents may indirectly help reduce the hazards of carbon monoxide by providing a more comfortable environment within the tent thereby reducing the incentive to restrict the ventilation of the tent. Water accumulation by the tents was found to be larger than expected, possibly due to the warmer than expected weather during field trial.

RÉSUMÉ

L'isolation et les taux de ventilation requis pour les petites tentes ont été analysés et comparés aux observations faites en laboratoire et à pied d'oeuvre sur deux prototypes de tentes lors d'essais d'hiver. Les valeurs de résistance thermique prévues concordaient bien avec les valeurs mesurées, mais il a été noté cependant que les techniques de fabrication peuvent modifier de façon marquée l'isolation thermique d'une tente. Les taux de ventilation ont donné lieu à deux analyses, l'une fondée sur la conservation de l'énergie thermique, l'autre sur l'analyse de l'écoulement dans un tuyau par poussée aérostatique. Les taux de ventilation prévus correspondaient aux taux mesurés à un facteur inférieur à deux dans des conditions calmes. Une estimation du taux de ventilation minimal acceptable a été calculée par analyse de combustion stoechiométrique d'un hydrocarbure type. Dans le cas des tentes isolées à l'étude, on a noté que ce taux minimal de ventilation pouvait être atteint par simple convection naturelle. Il est possible que ce ne soit pas le cas des tentes non isolées où les températures de l'air ne sont pas suffisantes. La mesure des niveaux de monoxyde de carbone réalisée durant le chauffage des tentes soumises aux essais d'hiver indique que ces niveaux se situaient nettement dans les limites acceptables et souvent même dans les limites d'exposition permises dans le cas du public. De façon indirecte, l'emploi de tentes isolées peut réduire les dangers du monoxyde de carbone car l'intérieur est plus confortable, réduisant ainsi la tendance à vouloir y restreindre la ventilation. On a aussi noté que l'accumulation d'eau était plus élevée que prévu, possiblement en raison de conditions atmosphériques moins rigoureuses qu'envisagées lors des essais sur le terrain.

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GLOSSARY

A	area, (m^2)
d	pipe or vent diameter, (m)
c_p	specific heat at constant pressure, (J/kg K)
g	gravitational acceleration, 9.8 (m/s^2)
h_L	fluid head loss coefficient, (m)
k	thermal conductivity, (W/m K)
m	mass flow rate, (kg/s)
M_{CO_2}	rate of production of carbon dioxide, (kg/s)
n	number of moles of a chemical species
ΔP	pressure difference, (Pa)
q	ventilatory heat loss rate, (W)
Q	heat transfer rate or thermal power, (W)
r	thermal resistance, (m^2 K/W)
R	thermal resistance, (K/W)
t	thickness, (m)
T	temperature, (C or K)
v,V	velocity, (m/s)
z	vent elevation, (m)
α	empirical radiative heat transfer constant, (m^2/kg)
ρ	density, (kg/m^3)
μ	viscosity, (kg/m s)
σ	Stefan-Boltzman constant, 5.67×10^{-8} (W/m^2K^4)

Subscripts

a	ambient
A	air
b	average batting property
bl	boundary layer
s	supplied to the tent interior air
t	thermal property or characteristic
T	tent wall
v	vent
vw	volume weighted average
1	ambient or inlet conditions
2	internal tent or discharge conditions

1.0 INTRODUCTION

Tents are frequently used as temporary shelters by both civilian and military personnel, especially in cold weather. For cold weather operations, tents may be insulated to improve their performance as a shelter from the environment. Insulated or not, tents used in cold weather give rise to certain problems which often reduce their over-all performance.

The amount of thermal insulation offered by the tent is an important consideration for a tent which is to be used in cold weather. The most common method of insulating a tent is to place additional fabric layers on either one side or both sides of the main tent wall. These layers provide thermal insulation by reducing the radiative heat transfer and the conductive heat transfer components at the tent wall. Alternately, insulating materials such as fibrous battings may be used to reduce heat loss. The thermal resistance which may be attained depends upon the number of fabric layers or the thickness of the insulating battings which may be added to the tent. Limiting considerations are over-all tent weight and bulk, the complexity of the tent construction and the side-effects of additional layers.

The acceptable limits on the weight and bulk of a tent are governed by the users' requirements and to some extent the manufacturers' capabilities. Thus, it is not generally possible to make blanket statements on these considerations. The remainder of this report will explore the thermal requirements of insulated tents, the side-effects of adding insulation and the ventilation of heated tents.

Included in this report are field observations of the performance of two tents, insulated with a fibrous batting. The observations were made during the Defence Research Establishment Ottawa's (DREO) Trial Run [1,2]. This trial took place in Febuary 1986 along the west coast of James Bay. Three members of DREO's Environmental Protection Section travelled several hundred kilometers by snowmobile, encountering a wide range of weather conditions.

2.0 INSULATION REQUIREMENTS OF TENTS

The quantity of insulation chosen to maintain the interior of a tent at an acceptable temperature depends upon several design criteria: the difference between the ambient and inside air temperatures; the amount of power available to heat the tent; the size of the tent; the amount of ventilation achieved; and the thermal resistivity of the insulating material.

2.1 DESIGN CRITERIA

The ambient temperature is undoubtably the most uncontrollable of the variables mentioned above. In the southern and coastal regions of Canada, temperatures reach -30°C only occasionally, while in the prairie provinces, lows of -40°C are sometimes attained. In the more nothern latitudes, lows of -40°C are common and are sometimes maintained for several days in succession. Extreme lows of -50°C and below are occasionally observed in these regions. For most purposes, a design limit for the ambient temperature of -40°C should be adequate, if not extreme, and it will be the assumed design criterion for ambient temperature for this study.

The temperature inside the tent varies considerably with height but only slightly with lateral distance from the heater. In winter, the floor of the tent is often snow or ice, hence the maximum floor temperature is 0°C. If the floor is covered with an insulating layer, such as sleeping bags, spruce boughs or an insulated floor, this temperature may be increased.

The rate of heat loss from the tent to the floor is small, approximately 10% [3] of the total heat loss from the tent, even though ground temperatures of -25°C have been observed in exteme climates. The cooler floor temperature may, however, result in a sizeable heat loss from the tent's occupants due to both radiation and conduction. Sleeping bags, a usual component of the personal kit of a tent's occupants, can be used to advantage as floor insulation. For extreme cold environments, it is not

generally desirable to have a floor which is integral to the tent. Such a floor is often heavy, bulky and collects water which can subsequentally soak into clothing and sleeping bags. In cold, wet environments, it is desirable to provide a barrier between the wet ground and the inside of the tent. An integral floor will still suffer from the draw-backs mentioned above. Ground-sheets or sleeping bags with waterproof bottoms are possible alternatives to integral floors.

When tents with integral floors are heated, the floor may billow upwards due to the lower pressure inside the tent. This phenomenon can be circumvented by puting a small vent in the floor. This source of fresh air may be useful in maintaining air quality within the tent, although, it will depend upon the air permeability of the ground below the tent and hence should not be counted on. For the purposes of this report, this flowrate will be assumed to be negligible. A wall-to-wall, integral floor could eliminate this potentially useful source of fresh air.

To provide a relatively comfortable environment, given that the tents occupants may make use of some parts of their cold weather clothing, an average internal air temperature of 15°C was chosen as a design criterion. Wall surface temperature is also important as radiant cooling of the occupants will occur if the tent walls are cooler than the surface temperature of the occupants. Radiant heat loss and conductive heat loss from clothing or skin are of comparable importance at low air velocities. If the thermal resistance of the tent walls is increased, the temperature of the inner surface of the walls will approach the local internal air temperature, reducing the radiant heat loss from the occupants.

The amount of power available with which to heat the tent will depend upon the amount of fuel which may be consumed and the stove used to burn the fuel. Several commercially available stoves which burn naphtha produce a maximum heat supply of approximately 2000 W while consuming 0.25 litres of naphtha per hour for each burner used. The stoves used on Trial Run, the Optimus "Hiker 111" model, have the characteristics noted above.

When these stoves are used to heat water in covered pots, one-half of the heat produced by the stove has been observed to heat the water while the other half went to heat the surrounding air [4]. This figure will no doubt depend upon several variables, but, a water heating efficiency of 50% is a convenient figure. While cooking, it is customary to heat as much water as is required in the minimum time. Thus, if two stoves are used, each heating water, the net result as far as heating the tent is concerned, is the same as heating the tent with one stove. Therefore, a design criterion of having 2000 W of heat supplied to the tent is convenient for small tents.

The surface area of the tent will be a function of the required floor area, height and tent style. In order to minimize the weight and bulk of the tent, the surface area of the tent should be a minimum. This will probably produce the minimum heat transfer characteristics for a tent.

The required floor area will be a function of the number of occupants who are to sleep in the tent. A rectangular area, measuring 2 metres long and 0.75 metres wide would typically be sufficient for one person. In addition, some storage area for the stoves and rations is convenient. The tents used on Trial Run were designed for three people and had a floor area which was nominally 2.5 metres long by 2.7 metres wide. The extra floor space allowed storage of the stoves and food at the head of the tent, allowed for variations in pitching the tent, and allowed the occupants to keep the sleeping bags away from the walls. This last point is important as condensation on the lower portions of walls can readily be transfered to clothing or sleeping bags which come into contact with the walls. A peak height of 1.3 metres was judged to be the minimum which would allow an occupant to kneel while cooking or lighting a stove. For simplicity of construction and to provide sufficient useable headroom, a semi-cylindrical style of tent was used. Other styles of tent might have been used which would have reduced the surface area of the tent [5], but on the basis of past experience with a conical shaped tent, the savings were judged not to be worth the extra construction complexity for this trial.

The required rate of ventilation will depend upon the rate of oxygen consumption and the rate of production of combustion gases. The heat loss due to ventilation may be determined knowing the ventilation rate, the temperature difference and the physical properties of air: the specific heat and density. The mathematical relationship which gives the ventilatory heat loss is:

$$q = \Delta(C_{p_A} \rho_A V_A A_v T_A) \approx (C_{p_A} \rho_A V_A A_v)(T_{A2} - T_{A1}) \qquad (1)$$

In order to maintain a safe level of carbon dioxide in small tents, (explained more fully in secton 3.3) a ventilation rate of 0.016 kg/s was deemed a minimum. It should be noted that if carbon monoxide is present, this ventilation rate may be inadequate. During Trial Run, there was no mechanism by which the ventilation rate could be varied with quantitative knowledge, and so the tent was ventilated so that the occupants felt no discomfort from either the air quality or air temperature within the tent. For design purposes, a ventilation rate of 0.016 kg/s was assumed. This results in a ventilatory heat loss of approximately 1000 W. This heat loss, subtracted from the total heat production of 2000 W leaves 1000 W for heat loss by other means.

The air temperature in the tent may be assumed to vary from a bulk temperature a few centimeters from the walls to the wall temperature immediately adjacent to the walls. The heat transfer to the walls from the air is proportional to the air temperature gradient at the wall. Although

this temperature gradient is often unknown, an adequate approximation for simple analyses is to attribute a thermal resistance to the air boundary layer along the wall. The actual details of the heat transfer are neglected, and the magnitude of the heat transfer is given by the difference between the bulk air temperature and the wall temperature divided by this thermal resistance. A rule of thumb for the value of the boundary thermal resistance which has been found to be applicable in low air flow rates is 0.1 m^2K/W [6]. In flows with high velocities (for example moderate winds), the thermal resistance is assumed to be zero.

With all of the preceeding information, it is possible to compute a required thickness of thermal insulation:

$$t_b = k_b((A_T\ (T_{A2} - T_{A1})/(Q_s - q)) - r_{b1}) \qquad (2)$$

For this computation, the heat loss to the floor has been neglected, althought it accounts for approximately 10% of the conductive and radiative heat loss from the tent. This value of thickness would be a minimum value as higher ventilation rates may occur due to the wind resulting in a larger ventilatory heat loss.

2.2 TENTS USED DURING TRIAL RUN

The tents used on Trial Run were insulated with Polarguard. Two thickness were readily available, 3 cm and 4.5 cm. The 3 cm thick sample had an aluminized, rip-stop polyester film bonded to one side which acted as a vapour barrier [5].

The thermal conductivity of battings has been found to be temperature dependent [8,9,10]. For the tents used on Trial Run the thermal conductivity of the material may be calculated approximately using the following semi-empirical equation [6]:

$$k_b = k_A + \frac{4\sigma}{\alpha\ \rho_b} T_b^3 \qquad (3)$$

Using equations 1 and 3, the design criteria noted above and a value of 1.5 m^2/kg for α (determined experimentally), the necessary thickness for the insulating material was determined to be approximately 4.0 cm. Because of other construction considerations, it was decided to make two tents: tent 1 with a nominal insulation thickness of 3 cm and tent 2 with a nominal insulation thickness of 7.5 cm, a combination of the two available thicknesses of battings.

The thermal resistances of the tents were calculated from material properties with a few approximations. Firstly, the heat transfer to the floor of the tents was assumed negligible. Secondly, an average insulation thickness was assumed based on thickness measurements of pitched tents. Thirdly, the thermal insulation of the doors of tent 2 was assumed to be due entirely to the boundary layer thermal resistance.

As noted in Section 2.1, the heat loss to the floor from the air in the tent should be less than approximately 10% of the total heat loss of the tent.

The thickness of the insulation in each of the tents was measured when the tents were pitched. The measurement of the tent wall thickness was estimated to be no better than 0.5 cm. The wall thickness for tent 1 was found to be approximately 1.4 cm near the seams and varied between 2.3 and 3 cm in the middle of the wall. The wall thickness for tent 2 was found to about 4 cm near the seams, between 5.3 and 5.8 cm in the middle of the walls, and 3 cm in a few highly stressed regions of the tent walls. The nominal thickness of the insulation for tents 1 and 2 were 3.5 and 7.5 cm respectively.

The difference between the actual and nominal insulation thicknesses is thought to be due to the tent construction techniques and the way in which the tents were pitched. The outer and inner fabric layers of the wall are sewn together at the circumferential seams at the ends of the tent, around the bottom and along a circumferential seam in the middle of the main tent wall. Both layers are under tension when the tent is pitched very taut, which compresses the fibrous batting thereby reducing its effectiveness as a thermal insulator. This problem can be solved, at the expense of increased construction complexity, by using a baffle arrangement or by suspending the liner so that the tension carried by the fabric layers has no or little normal component of force on the batting and hence the batting remains uncompressed. Even using a slightly larger liner would alleviate much of the problem.

Variations in the thickness of the insulation of the tent affect the resulting, effective thermal resistance. The effect of the variation in thickness is to produce a number of parallel paths for heat loss through the tent walls. An effective thickness of insulation was calculated for each tent using the Furbikini principle [4] where area weighted, inverse thickness of regions of the tent walls are averaged.

The thermal resistances for the walls of the two tents where calculated using approximate wall thicknesses of 2.3 cm for tent 1 and 4.5 cm for tent 2. The values obtained where 0.5 and 1.0 m^2K/W for tent 1 and tent 2 respectively. At the nominal wall thicknesses, the wall resistances would have been approximately 0.6 and 1.3 m^2K/W for tent 1 and tent 2 respectively.

Each of the three-man tents used on Trial Run was tested in the DREO cold-room. Internal air temperatures and ambient temperature were measured by thermistor. Air velocities at the inlet and discharge vents were measured by Hot Wire Anemometers (HWA). Heat was supplied at known rates from two electric heaters placed at one end of the tent, similar to the placement of stoves during Trial Run.

Thermal resistance of the tents were deduced experimentally as follows. It was assumed that the heat loss to the floor of the tent was negligible [3]. With all vents closed, air temperatures were measured at numerous points throughout the tent, and an average internal air temperature was established. For simplicity, a volume weighted average was used [7] although strictly the temperatures at the walls should have been determined and weighted according to wall area. The error introduced by this is approximately 3%. The ambient temperature was recorded along with the rate of heat input to the tent. Thus, the thermal resistance of the tent was calculated by:

$$R_t = (T_{vw} - T_a)/Q_s \tag{4}$$

During the experimental measurements in the DREO cold-room, the outside surface temperatures of the tents where examined with a pyrometer. As expected the walls had a temperature which was close to the ambient air temperature, however, the doors of tent 2 were observed to have a temperature which was intermediate to the internal and ambient air temperatures. This was not observed with the doors of tent 1. This would seem to indicate a poor seal around the insulating door flaps of tent 2, possibly due to the way in which the tent was pitched or possibly due to a design fault.

The result of the poor seal was that a section of the wall had a lower thermal resistance than the thermal resistance calculated above. In an attempt to take this into account, it was assumed that the thermal resistance of the doors was only 0.1 m^2K/W (that being the thermal resistance attributed to the boundary layer on the inner surface of the door). The doors represent 1 m^2 of the total 15 m^2 of the tent surface area. The thermal resistance of the doors and the tent walls where then added in parallel. The values for the overall thermal resistance of the tents obtained by this procedure agreed with the values obtained experimentally to within 12% and are shown in Table 1.

The accuracy in the calculation of the wall thermal resistance is expected to be about 15 to 20%, with errors occuring due to the accuracy of the wall thickness measurements, the approximations used for the door thermal resistance and the disregarded heat loss to the floor. The accuracy in the experimental evaluation of the thermal resistance is expected to be about the same, with sources of error arising in the evaluation of the heat input rate and the average internal air temperature.

Table 1. Laboratory measurements of heat input and resulting temperatures in the tents which were used on Trial Run. Calculations include an estimate of the reduced door insulation for tent 2. No ventilation.

Tent	Test Number	Heat Input (W)	Internal Temperature (°C)	Ambient Temperature (°C)	Thermal Resistance Calculated (K/W)	Thermal Resistance Measured (K/W)	Deviation (%)
1	1-1	1207	64.5	24.9	0.0282	0.0329	-14
	1-2	1207	29.6	-21.7	0.0353	0.0425	-17
	1-3	2307	57.9	-21.3	0.0326	0.0340	- 4
2	2-1	1173	72.5	28.5	0.0387	0.0375	+ 3
	2-2	1173	33.5	-20.9	0.0446	0.0463	- 4
	2-3	2295	65.3	-21.0	0.0428	0.0376	+14

Table 2. Average internal tent temperatures with the vents opened in laboratory tests and in field measurements.

Tent	Test Number	Heat Input (W)	Internal Temperature (°C)	Ambient Temperature (°C)
1	1-4	1207	63.6	+28.6
	1-5	1207	29.7	-21.6
	1-6	2307	46.1	-20.8
	Field	2000	16.1	-28.5
2	2-4	1173	66.9	+29.0
	2-5	1173	22.7	-21.0
	2-6	2295	44.6	-20.9
	Field	4000	33.5	-28.0

3.0 VENTILATION RATES

Ventilation of tents in the field is normally achieved solely through natural convection although the wind may induce forced convection if it happens to impinge on an open vent. In general, excess ventilation is preferred to insufficient ventilation. Excess ventilation results in a reduction of maximum attainable average air temperature in the tent. Insufficient ventilation could result in dangerous levels of combustion products from gas burning heaters, including the production of carbon monoxide if incomplete combustion occurs.

3.1 LABORATORY MEASUREMENTS

Ventilation rates were found from laboratory measurements by three different methods.

The first method was a calculation based on the conservation of thermal energy. The thermal resistance of the tent was determined experimentally, the volume weighted temperature difference between the tent and the environment was calculated from measurements and the heat input to the tent was known. The ventilatory heat loss is:

$$q = m_A c_{p_A} (T_{vw} - T_a) = m_A c_{p_A} \Delta T \tag{5}$$

The amount of heat lost by ventilation can be estimated from the difference between the heat supplied to the tent and the heat loss through the walls (calculated from the thermal resistance obtained by equation 4). Then equation 5 can be rearranged to yield:

$$m_A = \frac{Q_s}{c_{p_A} \Delta T} - \frac{1}{c_{p_A} R_t} \tag{6}$$

The second method was based on a fluid mechanics analysis of the flow through the tent. The driving force or pressure difference is generated by the density difference between the air inside the tent and the air outside the tent due to the different temperatures. The driving force is then:

$$\Delta P = (P_1 - P_2) = (\rho_1 - \rho_2)g(z_2 - z_1) = (\rho_1 - \rho_2)g\Delta z \qquad (7)$$

As the vents are relatively short, frictional loses within the vents should be small. Also, since the characteristic tent length is so much larger than the vent diameter, the tent may be represented as a reservoir. Thus the loses incurred by flow are, approximately, the entrance and exit loses of each of the vents. The inlet vent was modeled as a re-entrant pipe while the discharge vent was modeled as a square-edged connection. Traditional, semi-empirical head loss coefficients for the inlet and discharge vents when modeled in this way are then [11]:

$$h_{L1} = (0.8 + 1.0)v_{A1}^2/2g \qquad (8a)$$

$$h_{L2} = (0.5 + 1.0)v_{A2}^2/2g \qquad (8b)$$

where the first numerical coefficient is due to losses associated with the flow entering a pipe from a reservoir and the second numerical term is the loss of kenetic energy of the flow as it is decellerated when it enters a reservoir. As the sections of pipe are short, frictional losses are assumed negligible.

If the flow can be assumed to be steady, then the pressure drop across tent is equal to the sum of the pressure drops across the inlet and discharge vents. These individual pressure drops may be computed from the head loss terms of equations 8a and 8b by:

$$\Delta P = \rho_{A1}g\ h_{L1} + \rho_{A2}g\ h_{L2} \qquad (9)$$

By conservation of mass, the inlet and discharge velocities are related by:

$$v_{A2} = v_{A1}\rho_{A1}A_{v1}/\rho_{A2}A_{v2} \qquad (10)$$

Using equations 7 to 10, and noting that the vent diameters are the same, the inlet flow velocity can be found to be:

$$v_{A1} = \{[1.11\ g\ \Delta z(1-\rho_{A2}/\rho_{A1})]\ /\ [1 + 0.833(\rho_{A1}/\rho_{A2})]\}^{\frac{1}{2}} \qquad (11)$$

This can then be used to calculate the inlet mass flow-rate from:

$$m_A = \rho_{A1} v_{A1} A_{v1} \qquad (12)$$

The third method used to estimate the ventilation rate was to measure the air velocity in the vents using a Hot Wire Anemometer (HWA). The HWA's were placed at the centre-line of the vents at the inner surface of the tent. If the flow through the vents is slow, the flow will be laminar. Flows can be characterized by using a non-dimensional parameter called the Reynolds number. The Reynolds number is the ratio of the inertial forces to the viscous forces within the flow ($Re = \rho Vd/\mu$). At low velocities, with Reynolds number less than approximately 2000 the flow will be laminar. As the velocity increases, and the Reynolds number increases beyond 2000, the flow will begin to become turbulent. Laminar and turbulent flows have quite different velocity profiles. The laminar flow, velocity profile is parabolic while the turbulent flow, velocity profile is much blunter and becomes increasingly blunt with increasing Reynolds number [11,12]. The centre-line velocity can be related to the mean velocity exactly for laminar flow, and approximately for turbulent flow.

In laminar flow, the mean velocity is one-half of the centre-line velocity. In turbulent flow, since the profile is blunt, the centre-line velocity is approximately equal to the mean velocity. This will over-estimate the mean velocity but the approximation becomes more precise as the Reynolds number increases. This results in a simple expression for the mass flow rate:

$$m_A = \rho_{Ai} v_{Ai} A_{vi}/2 \quad , Re \quad 2000 \ \text{(laminar)} \qquad (13a)$$

$$m_A \approx \rho_{Ai} v_{Ai} A_{vi} \quad , Re > 2000 \ \text{(turbulent)} \qquad (13b)$$

where i equals 1 or 2, refering to the entrance or discharge vent respectively.

The first method, using thermal energy conservation, is the easiest to apply, especially in the field, once the tent characteristics are known. The second method, using a pipe flow analysis, is only valid for natural convection ventilation and may be inappropriate for use in the field if the wind is blowing. The third method, using hot wire anemometers or other comparable air velocity meters, are easily applied in either laboratory or field studies, although, hot wire anemometers are delicate and may be unsuitable for the rigors of field studies.

Table 3 shows the mass ventilation rates as calculated by these three techniques. There is some scatter in the results, however, the mass flow rates are similar in most cases. The analysis indicated that the Reynolds number was always greater than 2000, indicating turbulent flow and as such equation 13b should be used. The discharge mass flow rate calculated by the third method seems significantly larger than the inlet mass flow rate and the mass flow rates calculated by the other two methods. These readings may be unreliable as the discharge vent and the discharge HWA were positioned directly above the electric, forced-air heaters. Irregular air movement may have introduced errors in the measurement of the discharge air velocity.

The results noted in Table 3 would indicate that the ventilation rate can be estimated to within a factor of approximately 3.

Table 3. Experimentally Determined Ventilation Rates. Corresponding temperatures and heating rates are given in Table 2.

Tent	Test Number	Ventilation Rate (kg/s)			
		Method 1	Method 2	Method 3 Inlet	Method 3 Outlet
1	1-4	0.0041	0.0050	0.0039	0.0116
	1-5	0.0036	0.0071	0.0022	0.0126
	1-6	0.0050	0.0082	0.0076	0.0126
2	2-4	0.0043	0.0051	0.0063	0.0075
	2-5	0.0052	0.0071	0.0089	0.0102
	2-6	0.0084	0.0082	0.0122	0.0117

3.2 FIELD MEASUREMENTS

In the field, a tent will generally be exposed to the wind which can have a significant effect on the ventilation rate. The analysis of the effect of the wind on the ventilation has been proposed for a future project and will not be examined here at great length. Instead, this report will only provide an estimate of the relative importance of the wind induced ventilation with respect to the natural convection ventilation.

The field measurements recorded in Table 2 occured under conditions which were somewhat different from the laboratory measurements. In both cases, there were two discharge vents and two inlet vents open. For tent 1 the wind speed was approximately 16 km/h (4.4 m/s) while for tent 2 the wind speed was 40 km/h (11.1 m/s). The direction of the wind relative to the tent was not recorded, but, the tents were erected so that the wind was blowing on one end of the tent rather than the side of the tent. Thus, it can be expected that the wind was at a small angle of attack relative to the vent opening.

Ventilation rates for the field tests were calculated from the energy conservation and the bouyancy flow analyses. The bouyancy flow analysis results are listed under Natural Ventilation in Table 4. It was assumed that the flow rates predicted by the energy conservation analysis were close to the actual flow rates. The difference between these values and the values obtained from the bouyancy calculations where attributed to wind induced convection. These values are recorded in Table 4 under the heading of Forced Ventilation. It must be noted that this number is only representative of these specific conditions, and will depend considerably upon the wind direction with respect to the inlet and discharge vents.

From Table 4, the effect of the wind can be seen to be considerably different in the two cases. For tent 1, the wind was light, and its effect on the ventilation rate was only 20% of the total flow. For tent 2, the wind was somewhat stronger, and its effect was greater, being responsible for about 65% of the total ventilatory flow.

Table 4. Estimated ventilation rates from field measurements.
Tent 1: 2 stoves heating water; 4 vents open.
Tent 2: 2 stoves heating; 4 vents open.

Tent	Ventilation Rate (kg/s)		
	Total	Natural Ventilation	Forced Ventilation
1	0.0215	0.0170	0.0045
2	0.0462	0.0163	0.0299

3.3 COMBUSTION ANALYSIS AND VENTILATION

A stoichiometric analysis for a generalized hydrocarbon fuel can be performed which results in:

$$(CH_2)_n + \frac{3}{2} nO_2 \rightarrow nCO_2 + nH_2O \qquad (14)$$

A naptha burning stove with an energy output rate of 4 kW consumes approximately 9×10^{-5} kg/s of fuel. Thus, the rate of production of carbon dioxide, assuming a stoichiometric reaction, can be calculated from:

$$M_{CO_2} = (44n \text{ kg/kgmole}_{CO_2}) / (14n \text{ kg/kgmole}_{(CH_2)_n}) \times m_{(CH_2)_n} \qquad (15)$$

which results in a production rate of 2.8×10^{-4} kg/s of carbon dioxide. If, for example, a level of 1% by volume of carbon dioxide is assumed to exist in a tent at 15°C, the above input of carbon dioxide would have to be accompanied by 0.016 kg/s of fresh air. For an ambient air temperature of -40°C, this air flow rate corresponds to a ventilatory heat loss of approximately 990 W, a subtantial heat loss.

The estimated levels of carbon dioxide in the tents during Trial Run, assuming complete combustion, are shown in Table 5 for the ventilation rates noted in Table 4. The levels of carbon dioxide lie between 0.3 and 1% by volume. These levels would not normally be detected without appropriate instrumentation. Normally, a level of approximately 2% would be noticable [13]. No discomfort attributable to the air quality was observed during the trial, indicating low levels of carbon dioxide.

Table 5. Predicted levels of carbon dioxide present in the tents during trial Trial Run using ventilation rates of Table 4. (Total denotes both wind induced forced flow and natural convection may be present).

Tent	Flow type	Ventilation Rate (kg/s)	Carbon Dioxide (% by volume)
1	natural convection only	0.0170	1.0
	total	0.0215	0.7
2	natural convection only	0.0163	1.0
	total	0.0462	0.3

4.0 CARBON MONOXIDE

Carbon monoxide levels in the tents were recorded during Trial Run. This was more for the safety of the occupants rather than a scientific study. Carbon monoxide is produced by incomplete combustion of fuel, in this case naptha. When this occurs in a small enclosure such as a tent, with inadequate ventilation, the levels can quickly become dangerous. Carbon monoxide hazards have been examined by a number of investigators [14,15,16,17] and experienced inadvertantly by climbers [18] and explorers [19].

Carbon monoxide production can be a problem in all types of tents in which fuel is being burned as even a low concentration of carbon monoxide constitutes a health hazard. In particular, vapour barrier tents rely on ventilation through the vents to maintain the air quality. Conventional tents may have ventilation by diffusion through the tent walls although one study [17] shows high levels of carbon monoxide in a conventional tent. Acceptable levels of carbon monoxide exposures have been reported as [20]:

ideal public	0 to 6 mg/m^3	- 8 hour exposure
levels	0 to 15 mg/m^3	- 1 hour exposure
acceptable	6 to 15 mg/m^3	- 8 hour exposure
public levels	15 to 32 mg/m^3	- 1 hour exposure
acceptable	55 mg/m^3	- 8 hour exposure
occupational levels	440 mg/m^3	- 15 minute exposure

Ideally, there should be no production of carbon monoxide by the stoves. The problem has been observed to be more acute while cooking. The hypothesis is that the pot above the burner cools the flame sufficiently that incomplete combustion occurs, resulting in carbon monoxide [15].

The levels of carbon monoxide measured in the tents during Trial Run are shown in Table 6. The measurements were made using a portable carbon monoxide meter (Model AMC-11CO, Armstrong Monitoring Corporation, Nepean, Ontario, Canada). The data indicates that the levels of carbon monoxide experienced during Trial Run were within the acceptable occupational limits and frequently within the acceptable public levels. It is thought that the stoves were in good working order and that the ventilation rates were adequate.

Although the vapour barrier increases the carbon monoxide hazard, the insulation may help reduce it. Most of the problems arise, as noted above, while cooking. This means that less heat is available for heating the tent and thus the tent is cooler. In many of the carbon monoxide encounters noted above, the occupants have been cold, frequently tired and have closed the vents resulting in inadequate ventilation. If the tent is well insulated, less heat is required to maintain a comfortable temperature so there is less incentive to reduce the ventilation rate. Still, the insulation should not be relied upon to eliminate the increased carbon monoxide hazard of vapour-barrier tents. Education of the dangers and recognition of the early symptoms of carbon monoxide poisoning should be the first line of defence.

Table 6. Carbon monoxide levels recorded in the tents during Trial Run. Assumed air temperature was 15°C. Fuel consumption of the stove was approximately 0.25 l/hr. Cooking times are approximate.

Date	CO mg/m^3	Comments
15 Feb	18-22	- recorded after cooking for approximately 2 hours with two stoves.
16	8	- two stoves heating water for forty minutes after one half hour of just heating the tent.
	23-28	- two stoves after heating the tent for one hour followed by one stove heating water and one stove heating the tent for one half hour.
17	15	- two stoves boiling water, time unknown.
20	29-35	- two stoves heating water for two hours followed by two stoves heating the tent for one half hour.

5.0 WATER ACCUMULATION

One major problem of using tents in the cold is the accumulation of water as frost on the tent walls. This increases the weight and the packed volume of the tents. During a previous exercise, a conventional tent was observed to have gained 10 kg in 5 days under moderately cold conditions. Tents, similar to those used during Trial Run, used on previous exercises showed no increase in weight, indicating low water accumulation. This was not the case during Trial Run.

Table 7 shows the weights of the tents during the trial. The results indicate a substantial increase in weight of which only a small portion can be accounted for by measurement error.

Table 7. Recorded weights of the tents used on Trial Run. Weights were recorded the morning of the dates indicated. Typical use was 2 to 3 hours heating water for supper, 2 hours heating, 3 persons sleeping 8 hours, 2 hours heating water for breakfast, 0.5 hour heating. The number of stoves used varied. Initial weights: Tent 1 - 7.1 kg; Tent 2 - 9.7 kg.

Tent	Day	Weight (kg)	Ambient Temperature max (°C)	min
1	15 Feb	7.6	-10	-33
	16	8.2	-20	-30
	17	8.9	- 4	-31
	18	9.5	- 1	-12
	19	10.0	-12	-16
2	19 Feb	10.0	-12	-16
	20	10.9	-13	-25
	21	10.0	-16	-33
	22	12.0	- 7	-20

There are significant differences between the conditions of this trial and the conditions of previous exercises. Less time was spent in the tents during Trial Run than on previous exercises. This meant that the tents were heated for shorter periods allowing less time to dry the tent, while comparable times were spent cooking and sleeping in the tents.

During Trial Run, there were days which were quite warm during which the tents could have picked up water from the snow at the floor of the tent. On previous exercises, the temperatures were consistantly colder so that the floor melting was never a problem. Daily water accumulations for both tents showed no discernable trends with the ambient temperature.

It is thought that the major location of water pickup occurred around the base of the tent. A possible solution may be to provide a water-proof, non-absorbing layer around the lower edge of the tent, both on the inside and outside surfaces.

6.0 CONCLUSION

Tents, insulated with fibrous battings, have been found to be both feasible and practible. Prediction of the minimum amount of insulation required is relatively straight-forward once the design criteria are established. These are: desired interior tent temperature, minimum ambient temperature, power available to heat the tent and the thermal resistivity of the insulating material. The equations used in this report assumed a minimum ventilation rate and its accompanying heat loss based on natural convection only. If forced convection occurs, the ventilatory heat loss will be greater and thicker insulation will be required.

The design of the tent should be such that loads carried by the main tent walls do not compress the fibrous batting, possibly by using baffles in an insulated wall or by suspending a liner from the single layer main tent wall. Special attention should be paid to the insulation of the doors as a poorly fitted thermal insulating layer on even a small area could substantially degrade the thermal insulating characteristics.

Two analytical methods for predicting ventilation rates were developed and compared with measured values obtained with Hot Wire Anemometers. The first method, which is based on a thermal energy balance for the tent, is capable of handling both natural and forced convection. The second method, which relies on the difference between the tent air density and the ambient air density for the driving potential, is only suitable for natural convection analyses. Under calm conditions, natural convection only, the two analytical methods and the measured values of ventilation produced comparable answers. Under field conditions, where the wind could play a significant role in the ventilation of the tent, the second method will underestimate the total flow-rate, however, the first method should produce a reasonable estimate of the ventilation rate.

Estimates of the effects of the wind on the ventilation rate where made based on two sets of field measurements. It was found that the wind could be the dominant mechanism for ventilatory flow, however, this is highly dependant upon the wind direction with respect to the tent and the wind speed.

A combustion analysis of a generalized hydrocabon fuel was performed, using a stoichiometric combustion and fuel consumption rates typical of small camping stoves which burn naptha. A mass ventilation rate of 0.016 kg/s of fresh air was found to be required assuming a 4000 W heat production (typical of two-burner stoves or two single-burner stoves) to achieve an arbitrarily assigned carbon dioxide level of 1% by volume for the tent. This was judged to be a minimum acceptable ventilation rate. Using the equations developed to predict ventilation rates, it was determined that the insulated tents used on Trial Run could be ventilated adequately by natural convection alone provided no carbon monoxide was being produced.

The ventilation rates attained during Trial Run were judged to be adequate based on both computations and the qualitative observations of the participants. This was under normal conditions with the stove in proper working order. Measured carbon monoxide levels, while within reportedly safe limits, were large enough to be of concern. These levels were observed both during and after cooking in the tent. A reduction in the ventilation rate or an increase in the carbon monoxide production rate could have produced unacceptable concentrations of carbon monoxide within the tent.

Insulated tents may indirectly lessen the hazards of carbon monoxide poisoning by attaining a comfortable interior temperature even with a substantial amount of ventilation.

The insulated tents used on Trial Run were approximately 1.25 m high. Each had two discharge vents at the highest point of the tent and two inlet vents approximately 0.5 m lower then this. The vents were all 10 cm in diameter. The ventilation rate due to natural convection could be increased by: increasing the height difference between the inlet and discharge vents; increasing the vent size; increasing both the number of inlet and discharge vents.

The height difference between the discharge and inlet vents is limited by the height of the tent for the discharge vents and the distance above the ground at which the inlet vents must be placed to ensure that no accidental blockage of the vent occurs. The ventilation rate is proportional to the square root of the height difference between the vents. The ventilation rate is linearly proportional to the vent area or number of vents of the same size and quadratically proportional to the vent diameter. Thus, increasing the vent diameter or size is the most effective way of increasing the ventilation rate followed by increasing the number of vents and increasing the height difference between the inlet and discharge vents.

The following information is typical of the tents used on Trial Run. A small tent having a surface area of approximately 15 m^2, insulated with long filament polyester battings, heated with a stove capable of producing 2000 W of heat should have a minimum batting thickness of approximately 4 cm when erected to produce an average internal temperature of 55°C above ambient. This temperature gradient should be sufficient to produce a ventilation rate of 0.016 kg/s to maintain a 1% by volume carbon dioxide concentration within the tent under ideal conditions. This should be adequate if there is no carbon monoxide production. If the stove is used for cooking, it should be assumed that carbon monoxide will be produced and steps must be taken to increase the rate of ventilation. Placing the tent so that the inlet vents face slightly into the wind may be sufficient to provide the necessary ventilation rate. As this extra ventilation will mean there is less power available with which to heat the tent, an insulation thickness somewhat greater than the 4 cm noted above would be desirable.

During Trial Run, the tents were observed to increase in weight, presumeably due to water accumulation. It was thought that this was due to some warm weather encountered on the trial and due to relatively short time spent simply heating the tents. This increase could possibly be avoided by using a water-proof, non-absorbing surface along the lower portion of the tent walls.

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Analyses of the insulation requirements and ventilation rates for small, insulated tents were made and compared with both laboratory and field observations on two proto-type tents used during a winter trial. Predicted values of thermal resistance were in good agreement with measured values, although it was found that construction techniques could significantly alter the value of thermal insulation for the tent. Two analyses of the ventilation rate were made, one based on the conservation of thermal energy and the second based on a bouyancy driven pipe flow analysis. Predicted ventilation rates agreed with measured values to within a factor of two under calm conditions. An estimate of the minimum acceptable ventilation rate was made based on a stoichiometric combustion analysis of a generalized hydrocarbon fuel. Observations of carbon monoxide levels, made while heating the tents during the winter trial, indicated that the levels where well within acceptable occupational levels and often within acceptable public exposure levels. Water accumulation by the tents was found to be larger than expected, possibly due to the warmer than expected weather during field trial.

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